$W^+ W^-$ Production Cross-Section Measurement at ATLAS

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On behalf of the ATLAS collaboration

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- WW analysis
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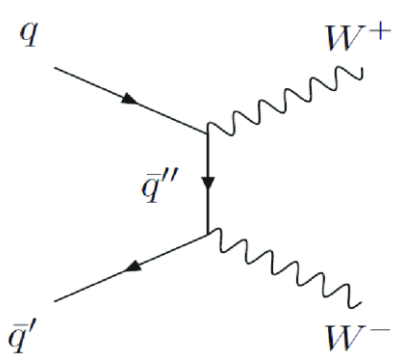
Introduction

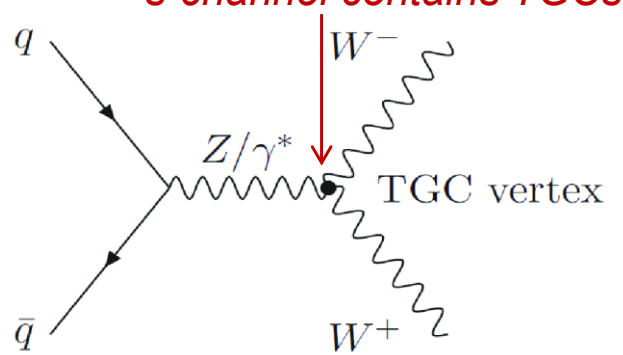
- Motivation
  - Test of the electro-weak theory (Triple Gauge Couplings) at the high energy frontier.
  - Search for new physics with anomalous TGCs.
  - Dominant background to $H \rightarrow W^+W^-$ search.
- W^+W^- production

$\sigma_{W+W-}^{NLO} = 46 \pm 3$ pb @7TeV p-p

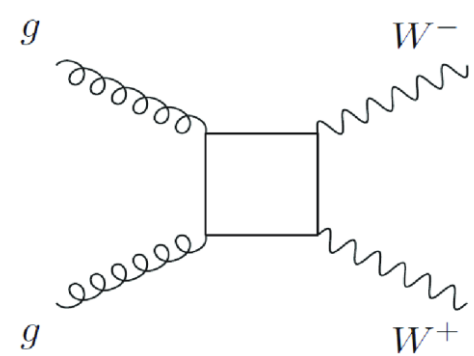
$q\bar{q}, q\bar{q}'$ initial states: ~97%



s-channel contains TGCs

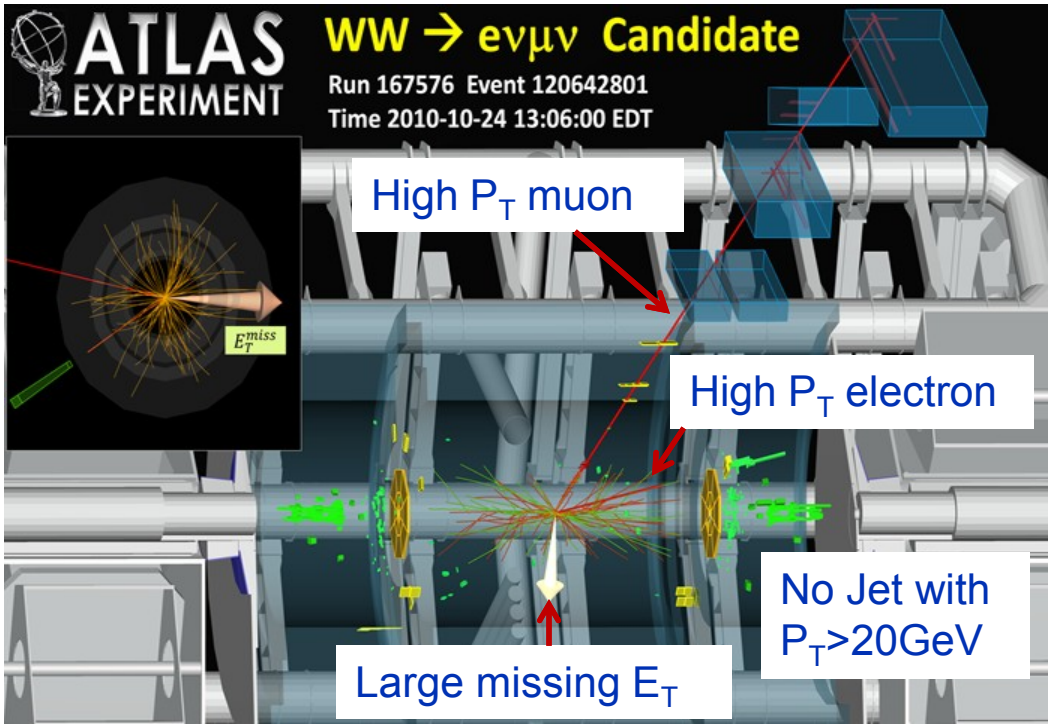


gg initial state: ~3%

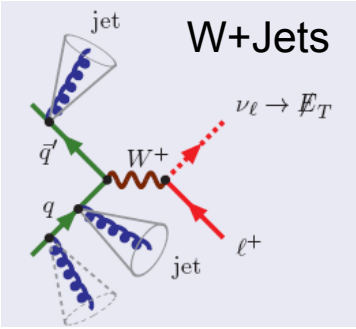


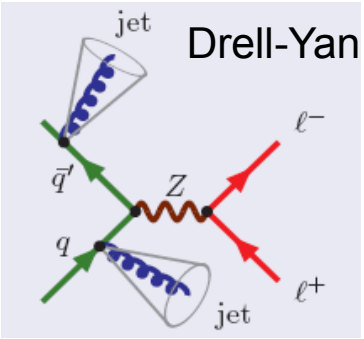
W^+W^- signature

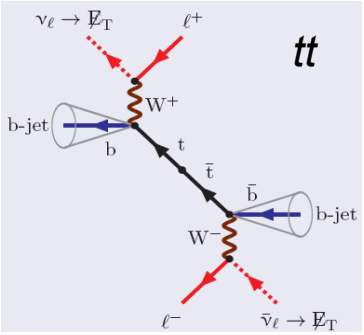
- Fully leptonic decays of both W's
  - $WW \rightarrow l\nu l\nu$ (l=e,μ) or
  - $WW \rightarrow \tau\nu\tau\nu \rightarrow l\nu l\nu$ (l=e,μ)
- Characteristics of final states
  - ✓ Two opposite-sign isolated high P_T leptons. Accordingly signal events are split into 3 channels:
    - ➢ **ee, $\mu\mu$, eμ**
  - ✓ Large missing E_T
  - ✓ Less jet activity



Main backgrounds







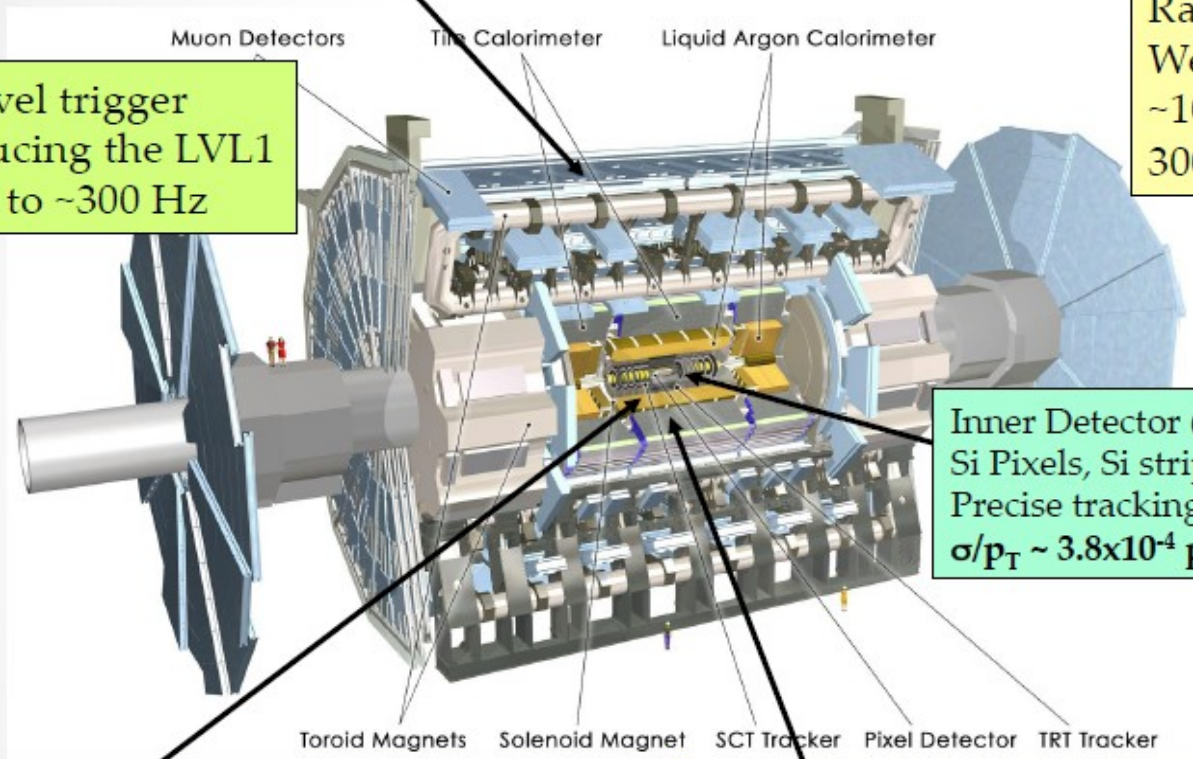
- **W+jets**
  - W leptonic decay produces a high P_T charged lepton and large missing E_T.
  - Associated jets can fake a second charged lepton.
  - Suppressed by lepton identification.
- **Drell-Yan**
  - high P_T charged lepton pairs produced from leptonic decays of Drell-Yan bosons.
  - Missing E_T either from mis-measurement of leptons or of associated jets, or from $Z \rightarrow \tau\tau$.
  - Reduced by Z mass veto and missing E_T cut.
- **Top**
  - *WW* pairs produced in *tt* or single top processes.
  - Rejected by vetoing on high-P_T jets.
- **Di-boson (*WZ,ZZ,W/Z+*γ)**
  - Leptons from boson decays or faked by photons.
  - Missing E_T from neutrino production or e/μ escape.
  - Removed by the criteria mentioned above plus the requirement of exactly two high P_T charged leptons.

ATLAS Detector

Muon Spectrometer ($|\eta|<2.7$) : air-core toroids with gas-based muon chambers **(MS)**
Muon trigger and measurement with momentum resolution **< 10% up to E_μ ~ 1 TeV**

Length : ~ 46 m
Radius : ~ 12 m
Weight : ~ 7000 tons
~10^8 electronic channels
3000 km of cables

3-level trigger reducing the LVL1 rate to ~300 Hz



Inner Detector ($|\eta|<2.5$, B=2T): **(ID)**
Si Pixels, Si strips, TRT
Precise tracking and vertexing,
σ/p_T ~ 3.8×10^{-4} p_T (GeV) $\oplus$ 0.015

EM calorimeter: Pb-LAr Accordion **(ECal)**
e/γ trigger, identification and measurement
E-resolution: σ/E ~ 10%/$\sqrt{E}$ $\oplus$ 0.007
High granularity

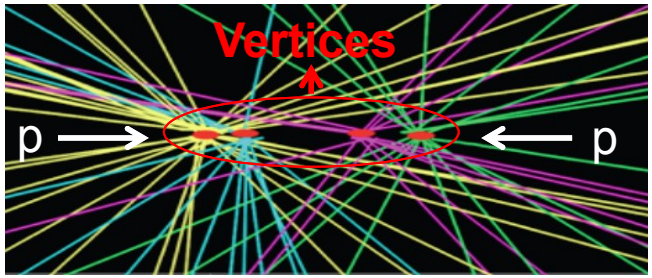
Hadron calorimetry ($|\eta|<4.9$) **(HCal)**
Fe/scintillator Tiles (central), Cu-LAr (endcap)
E-resolution: **σ/E ~ 50%/$\sqrt{E}$ $\oplus$ 0.03**
FWD calorimetry:Cu/W-LAr **σ/E ~ 90%/$\sqrt{E}$ $\oplus$ 0.07**

Trigger, Collision data and MC

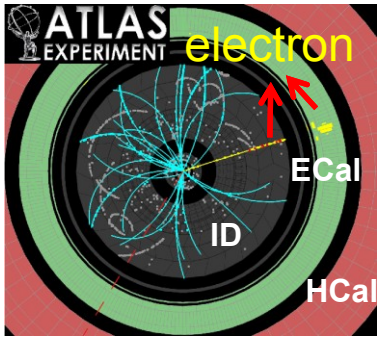
- **Trigger**
  - Single electron with E_T>15GeV or single muon with P_T>13GeV
  - Trigger efficiencies on plateau when $E_T(P_T)$>20GeV
  - Di-lepton ε_{trig}(data)/ε_{trig}(MC) consistent with unity
- **Collision data**
  - Only data recorded with all relevant sub-detectors fully operational are used.
  - Total: 35pb^{-1} of 7TeV pp collisions collected in 2010
- **MC samples**
  - Signal generation
    - $q\bar{q}, q\bar{q}' \rightarrow W^+W^-$: MC@NLO(CTEQ6.6)/HERWIG/Jimmy
    - $gg \rightarrow W^+W^-$: gg2ww/HERWIG/Jimmy
  - Background generation
    - W/Z+jets: ALPGEN, top/WZ/ZZ: MC@NLO, Wγ: Pythia
  - Detector simulation based on GEANT4
  - Pileup simulated by overlaying minimum bias MC events

Physics Objects

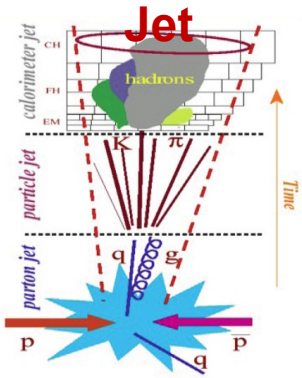
- **Vertex**
  - Reconstructed with ID
  - Primary vertex ($N_{tracks} \geq 3$ && max. ΣP_T^{Trk})
  - MC reweighted to reproduce the vertex multiplicity in data

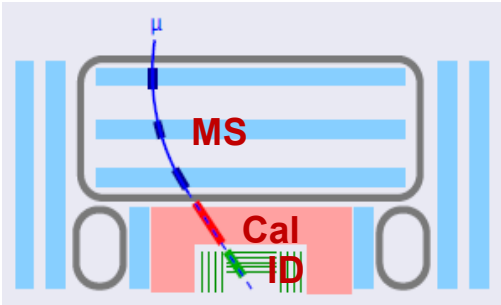


- **Electron**
  - Reconstructed and identified with ID+ECal(HCal)
  - E_T>20GeV, $|\eta|$<1.37 or 1.52<$|\eta|$< 2.47, E_T(cone0.3)<6GeV



- **Muon**
  - Reconstructed by associating a MS track with an ID track
  - P_T>20GeV, $|\eta|$<2.4, ΣP_T(cone0.2)/P_T^{μ}<0.1
- **Jet**
  - Reconstructed from calorimeter clusters using Anti-Kt algorithm with R=0.4
  - P_T>20GeV, $|\eta|$<3.0, ΔR(Jet, e)>0.3





- **Missing $\vec{E}_T$**
  - $\vec{E}_T^{miss}$ =-$\Sigma\vec{E}_T$(calorimeter clusters + muons)
  - Modified to be more powerful in background rejection (more in slide11)

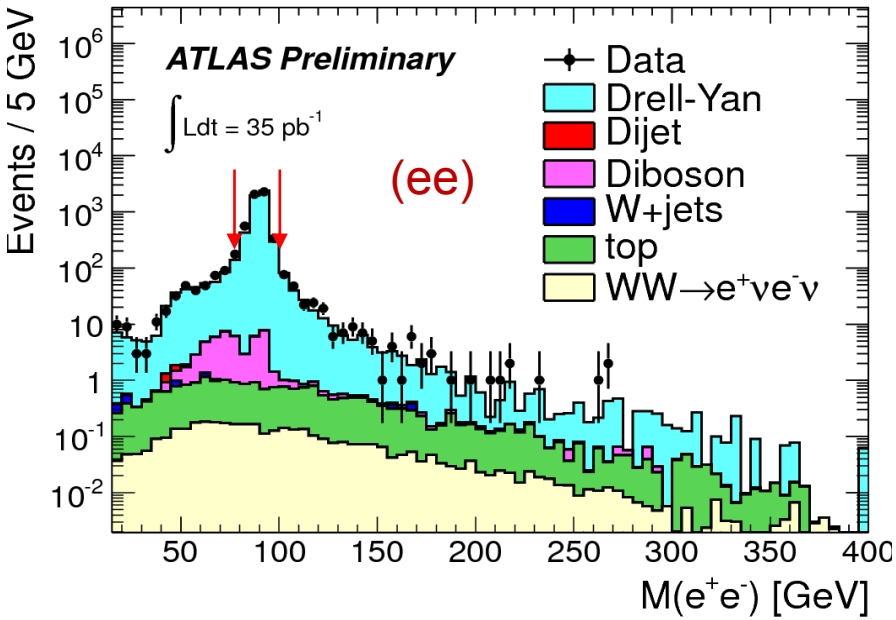
$$E_{T,\,Rel}^{miss} = \begin{cases} E_T^{miss} \times \sin(\Delta\phi_{\ell,j}) & \text{if } \Delta\phi < \pi/2 \\ E_T^{miss} & \text{if } \Delta\phi \geq \pi/2 \end{cases}$$

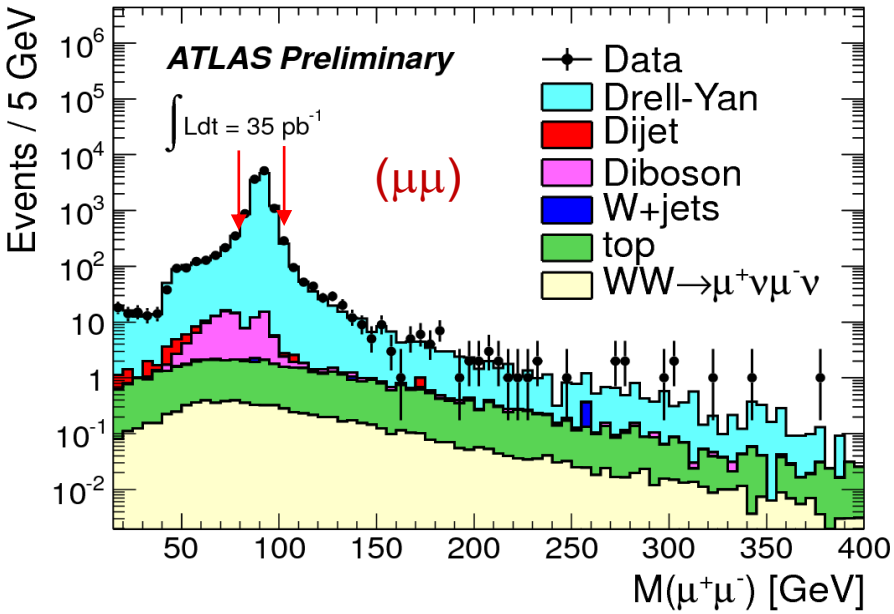
Event Selection

- **A good primary vertex and trigger selection**
  - To select interesting collision candidates
- **Exactly two opposite-sign good leptons (e,μ)**
  - To select di-lepton events
  - To suppress W+jets and di-boson events
- **M_{ll}>15GeV && $|M_{ll}-M_Z|$>10GeV for ee and μμ channels**
  - Mainly to remove Drell-Yan events
- **$E_T^{miss}{}_{Rel}$> 40GeV in ee and μμ channels, and >20GeV in eμ channel**
  - To further remove Drell-Yan and di-boson events
- **Jet veto : No jets (P_T>20GeV, $|\eta|$<3) present**
  - To remove top events

$M_{\ell\ell}$ after di-lepton selection

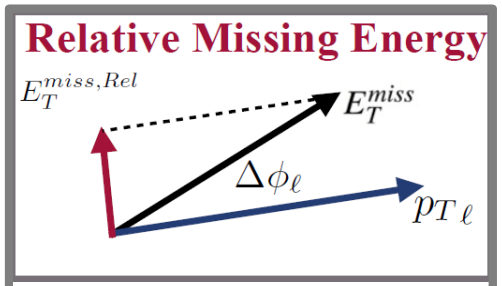
- >97% of the di-lepton events in ee, μμ channels are Drell-Yan background.
- Those background events can be largely removed by $|M_{ll}-M_Z|>10$GeV



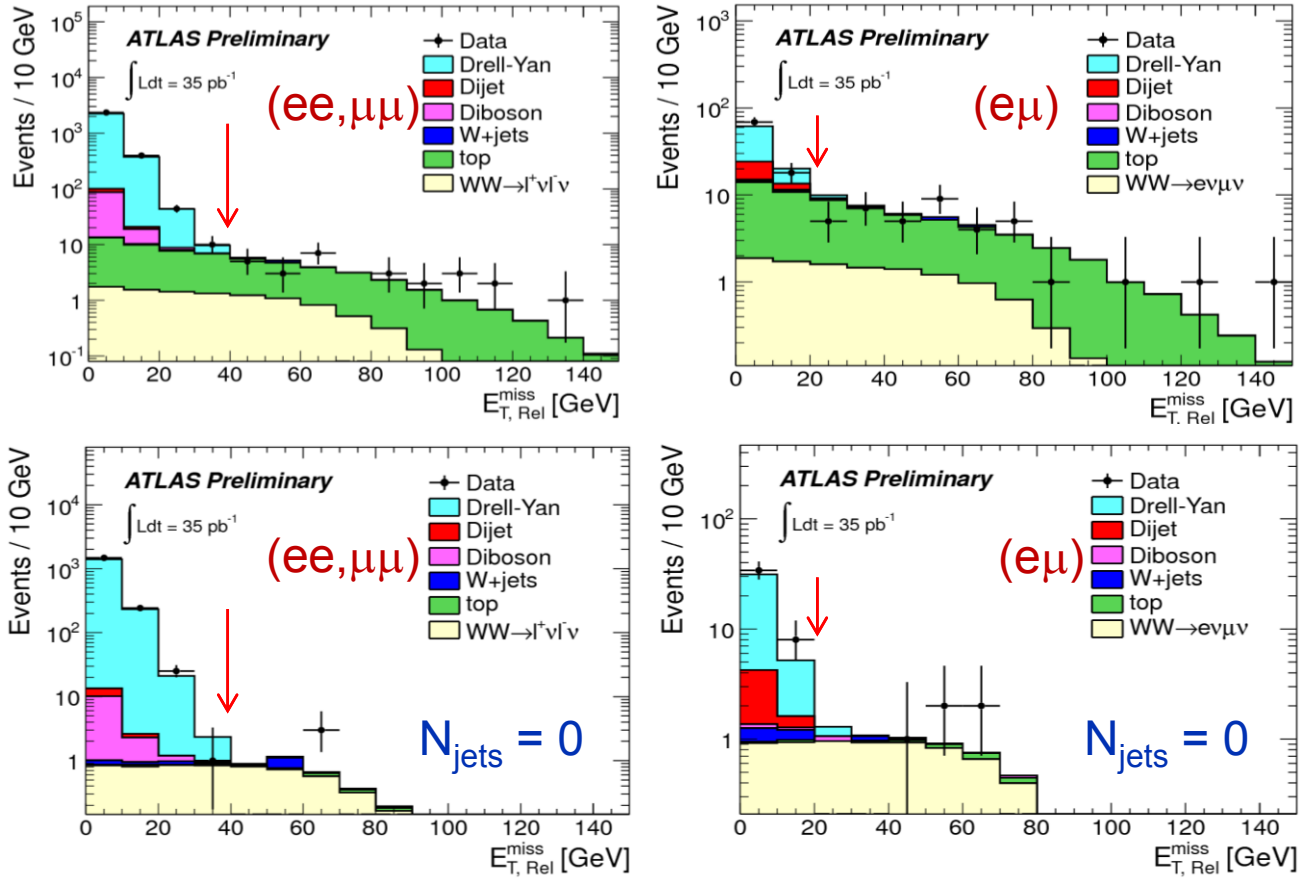


$E_t^{miss,Rel}$ after $M_{\ell\ell}$ cuts

- The remaining Drell-Yan background after the Z mass veto can be effectively further removed by cutting on $E_t^{miss,\ Rel}$.

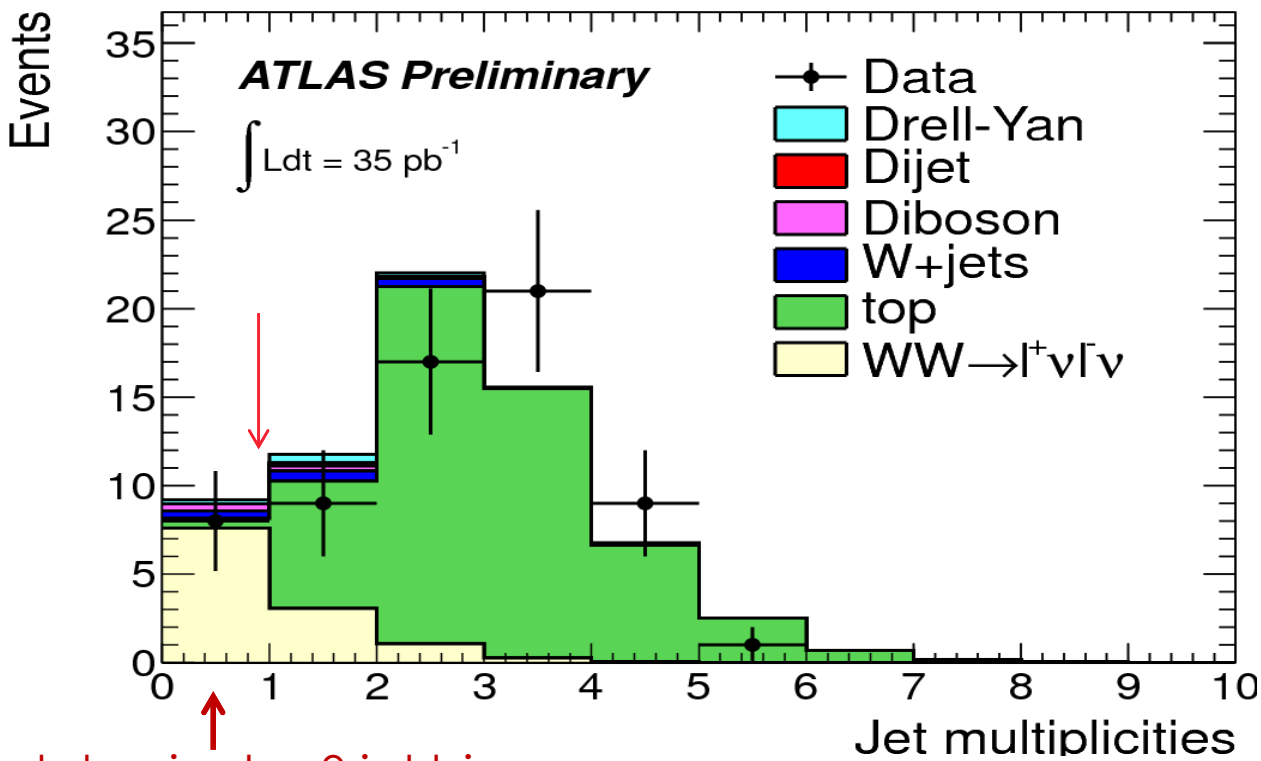


- less sensitive to mis-measured leptons or jets .
- higher sensitivity to real E_t^{miss} from neutrinos.
- Better signal-background ratio



Jet Multiplicity after $E_t^{miss,Rel}$ cut

- Most of the top background can be removed by Jet veto
  - $N_{Jets(P_T>20GeV,\ |\eta|<3.0)} == 0$



WW signal dominates 0 jet bin.

Number of W^+W^- candidates (data)

- Number of W^+W^- candidates in data after each major requirement in the event selection.

Cuts	$e^+e^- + E_T^{miss}$	$\mu^+\mu^- + E_T^{miss}$	$e^\pm\mu^\mp + E_T^{miss}$
2 leptons (SS and OS)	6096	12802	134
2 leptons (OS)	6057	12798	126
$M_{\ell\ell} > 15$ GeV	6044	12724	-
Z veto ($\lvert M_{\ell\ell} - M_Z \rvert > 10$ GeV)	872	1935	-
$E_{T,\,Rel}^{miss}$ cut	12	14	39
Jet veto (No. of jet=0)	1	2	5

Signal Acceptance

Cuts	$ee E_T^{miss}$ Channel		$\mu\mu E_T^{miss}$ Channel		$e\mu E_T^{miss}$ Channel	
	$e\nu e\nu$	$\tau\tau/e\tau\nu\nu$	$\mu\nu\mu\nu$	$\tau\tau/\mu\tau\nu\nu$	$e\nu\mu\nu$	$\tau\tau/\mu\tau/e\tau\nu\nu$
Total Events	18.99	7.27	18.99	7.27	37.98	14.55
2 leptons (opposite charge)	3.46	0.41	7.70	0.85	10.36	1.16
$M_{\ell\ell} > 15$ GeV & Z veto	2.93	0.34	6.43	0.69	10.36	1.16
$E_{T,\,Rel}^{miss}$ cut	1.21	0.11	2.76	0.21	7.17	0.74
Jet veto	0.78	0.07	1.63	0.12	4.38	0.43
Overall acceptance	4.1%	0.9%	8.6%	1.6%	11.5%	2.9%

- *All event numbers are normalized to the data integrated luminosity of 35pb^{-1} using the SM W^+W^- NLO cross-sections.*
- *All efficiency correction factors ($\varepsilon_{data}/\varepsilon_{MC}$) and the other corrections have been applied.*

Acceptance Uncertainty $\Delta A/A$

Source	Lepton ID	Jet-veto	Vertex reweighting	PDFs
$\Delta A/A$	4.2%	6.0%	0.5%	1.2%

Total $\Delta A/A$(ee,$\mu\mu$,$e\mu$ combined) **= 7.4%**

Background Estimation (I)

- Estimates of W+Jets and Drell-Yan backgrounds.

Source	Mean	Stat. Uncertainty	Syst. Uncertainty
W+jets bkg (ee)	0.08	0.05	0.03
W+jets bkg ($\mu\mu$)	0	0.29	0.10
W+jets bkg ($e\mu$)	0.46	0.12	0.17
W+jets bkg (total)	0.54	0.32	0.21
Drell-Yan bkg (ee)	0	0.10	0.07
Drell-Yan bkg ($\mu\mu$)	0.01	0.10	0.07
Drell-Yan bkg ($e\mu$)	0.23	0.06	0.15
Drell-Yan bkg (total)	0.24	0.15	0.17

W+Jets(Jet faking a lepton): Data driven estimation

$$N_{W+\text{jet Bkg}} = f_l \times N_{\text{lepton ID + Jet-Rich ID}}$$

→ From W+Jet control sample where W+Jet events are enriched due to looser lepton ID

$$f_l \equiv \frac{N_{\text{lepton ID}}}{N_{\text{Jet-Rich ID}}}$$

→ Fake rate determined using di-jet sample in data

Results cross-checked using the same-sign di-lepton sample in data.

Drell-Yan: Central values are estimated using MC. Systematic uncertainties are estimated using a data driven method on Z control sample (by looking at data/MC discrepancy in $E_t^{miss,Rel}$ distribution under Z peak)

Background Estimation (II)

- Top background estimated using MC and cross-checked using data driven methods.
- Di-boson (WZ, ZZ, W/Z+γ)backgrounds estimated using MC.

	ee	$\mu\mu$	$e\mu$	total
Top	0.04±0.02±0.03	0.15±0.06±0.08	0.36±0.10±0.19	0.55±0.12±0.30
Di-boson	0.05±0.01±0.01	0.10±0.01±0.01	0.24±0.05±0.03	0.39±0.04±0.06

Background summary

ee	$\mu\mu$	$e\mu$	total
0.17±0.11±0.09	0.26±0.31±0.15	1.29±0.17±0.32	1.72±0.37±0.45

N_b (ee,$\mu\mu$,eμ combined) = 1.7±0.6

Observation and Predictions

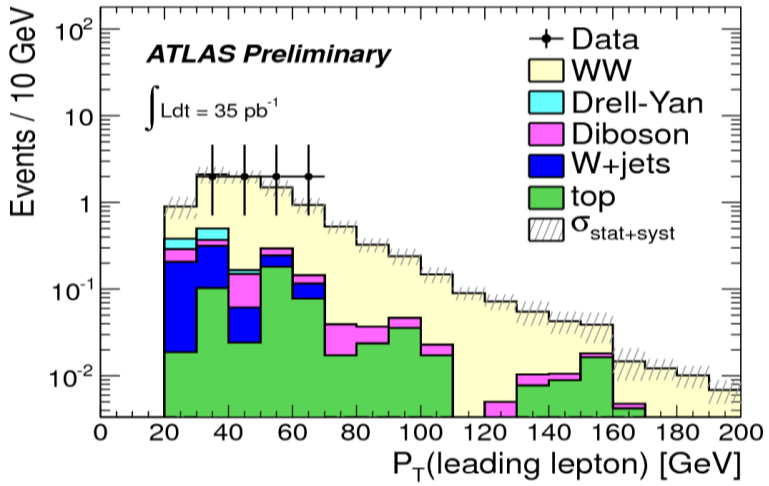
Final State	$e^+e^-E_T^{miss}$	$\mu^+\mu^-E_T^{miss}$	$e^\pm\mu^\mp E_T^{miss}$	combined
Observed Events	1	2	5	8
MC WW Signal	$0.85\pm0.02\pm0.13$	$1.74\pm0.04\pm0.24$	$4.81\pm0.06\pm0.68$	$7.40\pm0.07\pm1.05$
Total Background	$0.17\pm0.11\pm0.09$	$0.26\pm0.31\pm0.15$	$1.29\pm0.17\pm0.32$	$1.72\pm0.37\pm0.45$
Signal / Background	5.0	6.7	3.7	4.3

ee, $\mu\mu$, eμ combined

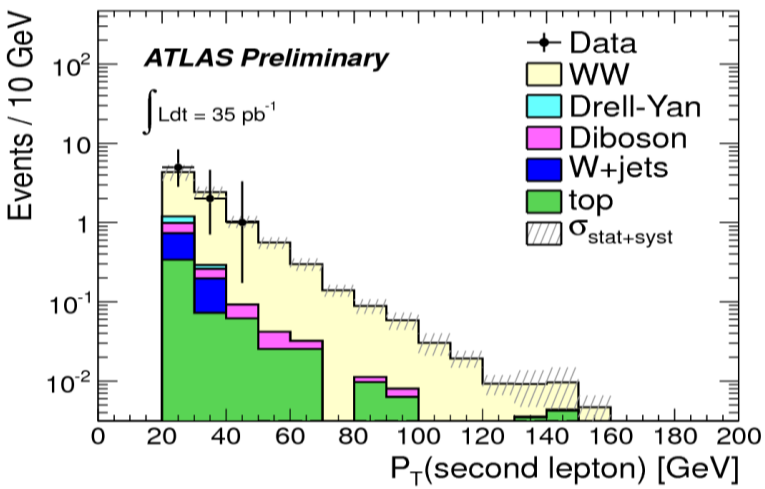
- $N_{observed} = 8$
- $N_{signal}=7.4\pm1.1$, $N_{background}= 1.7 \pm 0.6$
- Signal significance = 3σ (P-value $=1.4\times10^{-3}$)

Kinematic Distributions of the W^+W^- candidates

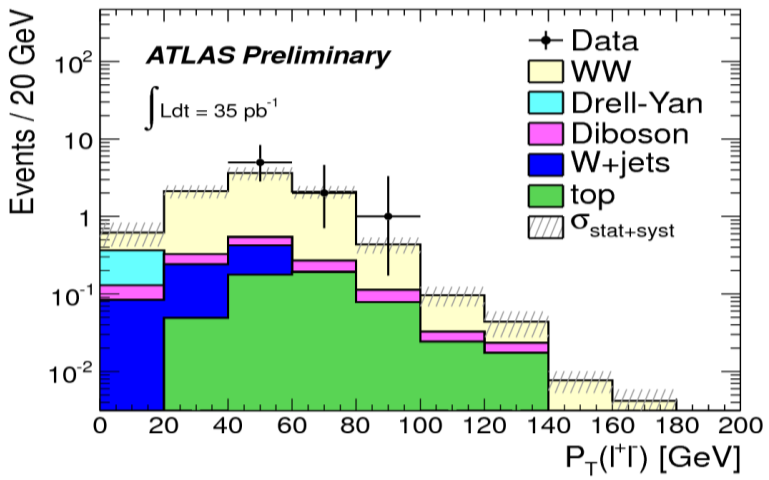
P_T of leading leptons



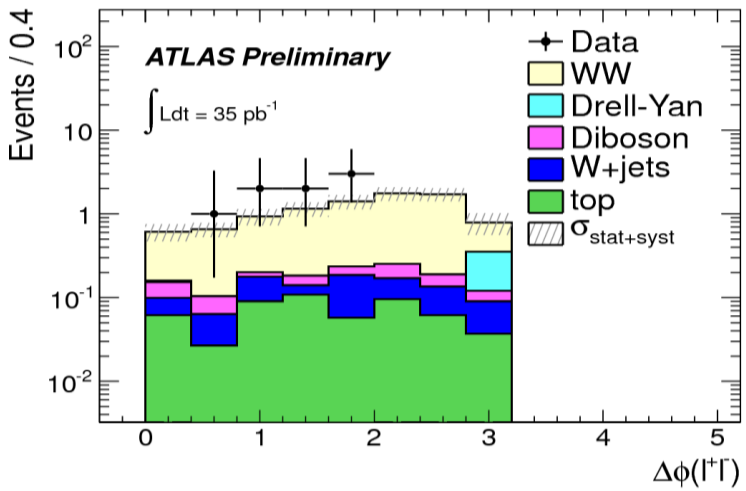
P_T of sub-leading leptons



P_T (l^+l^-)



$\Delta\phi(l^+l^-)$



W^+W^- production cross-section

- The combined W^+W^- production cross-section is determined using the maximum likelihood method. The likelihood function based on Poisson statistics is constructed as

$$F = \ln \prod_{i=1}^{3} \frac{e^{-(N_s^i + N_b^i)} (N_s^i + N_b^i)^{N_{obs}^i}}{N_{obs}^i !} \quad \text{where} \quad N_s^i = \sigma_{WW} \times Br^i \times \mathscr{L} \times A^i$$

- The systematic uncertainty is estimated simply using

$$\sigma_{syst}/\sigma_{WW} = \sqrt{(\Delta\mathscr{L}/\mathscr{L})^2 + (\Delta A/A)^2 + (\Delta N_b/(N_{obs} - N_b))^2}$$

($\Delta\mathscr{L}/\mathscr{L}$=11%, $\Delta A/A$=7.4%, $\Delta N_b/(N_{obs}-N_b)$=9.2%)

$$\sigma_{WW} = 40^{+20}_{-16}(\text{stat}) \pm 7(\text{syst})\ \text{pb}$$

(SM NLO prediction: 46±3 pb)

Summary

- The W^+W^- production cross-section in 7TeV p-p collisions has been measured with $\ell\ell + E_T^{miss}$ +0Jets final states using 35pb^{-1} of data collected by ATLAS in 2010.
- 8 W^+W^- candidate events observed and 1.7± 0.6 background events expected, corresponding to a signal significance of 3σ.
- The W^+W^- production cross-section measured to be

$$\sigma_{WW} = 40^{+20}_{-16}(\text{stat}) \pm 7(\text{syst})\ \text{pb}$$

  which is in good agreement with the SM NLO prediction of 46±3pb.
- The measurement is largely limited by statistics. The future analysis with larger dataset will be important for precision test of the SM and new physics searches.

Conference note for this measurement: ATLAS-CONF-2011-015